



Temperature and deactivation of microbial faecal indicators during small scale co-composting of faecal matter

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ABSTRACT

Small scale co-composting of faecal matter from dry toilet systems with shredded plant material and food waste was investigated in respect to heat development and deactivation of faecal indicators under tropical semiarid conditions. Open (uncovered) co-composting of faecal matter with shredded plant material alone did not generate temperatures high enough (<55 °C) to reduce the indicators sufficiently. The addition of food waste and confinement in chambers, built of concrete bricks and wooden boards, improved the composting process significantly. Under these conditions peak temperatures of up to 70 °C were achieved and temperatures above 55 °C were maintained over 2 weeks. This temperature and time is sufficient to comply with international composting regulations. The reduction of *Escherichia coli*, *Enterococcus faecalis* and *Salmonella senftenberg* in test containment systems placed in the core of the compost piles was very efficient, exceeding 5 log₁₀-units in all cases, but recolonisation from the cooler outer layers appeared to interfere with the sanitisation efficiency of the substrate itself. The addition of a stabilisation period by extending the composting process to over 4 months ensured that the load of *E. coli* was reduced to less than 10³ cfu^{-g} and salmonella were undetectable.

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1. Introduction

World-wide, 2.6 billion people are estimated to defecate in the open or in unsanitary places (WHO and UNICEF, 2006). The lack of adequate sanitary installations and proper sanitary waste disposal systems leads to serious implications on human and environmental health (Schaefer, 2008). Highlighted by the UN Millennium Development Goal target to 'halve by 2015 the proportion of people without access to basic sanitation', improved sanitation has become an issue of global importance.

Dry toilet systems are widely promoted as a suitable entry point to fulfil the sanitation target set in developing countries. A variety of techniques including ventilation, solar drying and urine diversion are integrated in these systems to allow continuous waterless operation (Esrey et al., 2001). The common feature of all dry toilet designs is the confined collection of faecal matter, preventing uncontrolled dispersal of pathogens and contaminants. Urine diverting dry toilets enable separate collection of urine and faeces in order to facilitate nutrient cycling. While urine has a relatively low pathogen content and is easily sanitised by storage prior to

usage as liquid fertiliser (Höglund, 2001), reduction of the inherent pathogen load of faeces is more demanding. Laboratory and bench scale composting trials have proven that heat generated by bacteria decomposing organic matter is apt to deactivate pathogens derived from the intestinal tract of humans (Niwaigaba et al., 2009; Vinneras et al., 2003). In large scale compost operations, sufficiently high temperatures are usually achieved over several days, although such a distinct thermophilic phase is not common in backyard composting (Illmer, 2002). The lower temperature development is likely to be associated with continuous addition of small amounts of low quality substrate. In small scale composting the physical and chemical conditions involved are known to be variable and apt to alter the results of the process unpredictably (Richard and Zimmerman, 1995).

However, decentralised small scale composting and local use reduces transport expenditure and improves competitiveness. This is an important aspect for developing countries and especially rural areas where insufficient financial liquidity limits farmers' willingness to pay for plant nutrient sources (Danso et al., 2006). Our research aims, therefore, to determine under local tropical conditions: (a) whether in simple small scale open composting sufficient sanitisation can be achieved by optimising the faecal matter to carbon source (shredded plant material) mixing ratio and the turning frequency and (b) if there is any significant advantage of substrate quality improvement, compost chambers and insulation.

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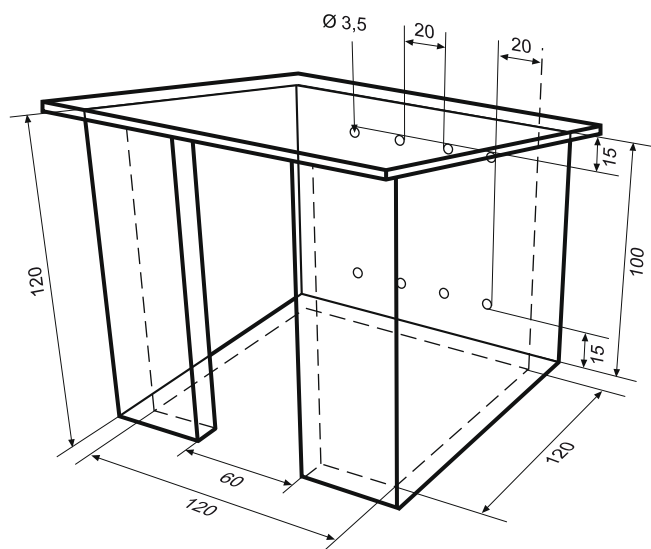


Fig. 1. Perspective drawing of the compost chambers with removable roof and door (not shown). All dimensions in cm. Drawing by Sylvia Fladderak.

2. Methods

2.1. Open composting experiment

The first trial was set up on the campus of Valley View University (VUU) in Oyibi and pseudoreplicated at Orphanage Africa (OA) in Ayeniah, both located in the Greater Accra Region of Ghana. Observations were conducted during the major rainy season from mid-May to early August 2007. The experimental design consisted of nine conical open (uncovered) compost piles of three different plant material to faecal matter ratios. These ratios were estimated prior to measurements to obtain a C:N ratio narrower than 1:30. The actual resulting C:N ratios were 10, 12 and 15 at VUU and 22, 22 and 23 at OA (Table 1). To reduce initial handling of raw faecal matter a sandwich set-up was chosen. The piles were stacked to a volume of about 1.5 m³ of alternating layers of shredded plant material and faecal matter, each with a thickness of roughly 10 cm. At both sites, all piles were thoroughly mixed after 7 days and from then onwards one pile of each of the three substrate ratios was turned every 3rd, 5th and 10th day.

2.2. Compost chamber experiment

The second experiment took place at VUU in 2008 with the beginning of the minor rainy season from mid-September to the end of January 2009. Four cubic compost chambers of about

1.5 m³ inner volume were constructed of concrete bricks (Fig. 1). The floor was left natural, while the doors and removable roofs were made of wooden boards. To avoid water penetration during heavy rains the roof was fitted with a pitch of 10° towards the back. Two chambers were left uninsulated and the other two were insulated with 5 cm thick styrofoam. In order to allow gas exchange four openings with a diameter of 3.5 cm each were integrated at the bottom and upper part of the back wall. Shredded plant material was mixed with faecal matter, food waste and saw dust at a dry matter ratio of 3.4:5.3:2.5:1.0. As no impact of different material ratios was observed in 2007 (Chapter 3.2) all chambers were filled with the same mixture in 2008. The compost volume was between 1.0 and 1.2 m³ per chamber and the C:N ratio 16 (Table 1). To study the impact of compost chambers on the temperature, temperatures were concurrently monitored in an open compost pile during the thermophilic phase. The substrate quantity and quality as well as the management of this pile were analogous to that of the chambers (Tables 1–3).

2.3. Substrate materials

The faecal matter used in the experiments was collected from two ventilated pit latrines. One is located at VUU and has been in use for over 10 years, collecting a mixture of faeces, urine and paper in a free draining cesspit. The second is located at nearby OA, equipped with solar-heated, bottom-sealed chambers and in operation for 5 years. Faeces, urine and paper are collected under addition of sawdust once a fortnight and wood ash once a month. None of the chambers had been emptied since the commissioning of the facilities. Content of C and K in the dry faecal matter was distinctly lower and of N and P higher at VUU in comparison with OA in 2007 (Table 2). In 2008 at VUU the C content was slightly higher, while dry matter, N and P, was lower than in 2007. Overall, the measured physiochemical parameters are comparable to that of faecal matter from dry toilet systems in Europe (Starkl et al., 2005).

Shredded plant material, dominantly *Panicum maximum* Jacq., leaves and twigs of *Azadirachta indica* A. Juss. and *Mangifera indica* L., was used as structure material and carbon source. In 2007 the properties of the shredded plant material were comparable at both sites except for the higher DM content at OA (Table 3). The plant material in the following year consisted of *P. maximum* and *Sorghum bicolor* (L.) Moench straw; both sun dried prior to composting.

The food waste used as additional co-substrate in 2008 consisted of rice leftovers, vegetable waste, peelings of plantain, yam and pineapple as well as scum from the grey water fat separator of VUU's cafeteria.

2.4. Temperature recording and humidity monitoring

In both years compost temperatures of the inner core and in the outer layer at about 10 cm depth were recorded twice daily as the mean of three individual measurements. Throughout the trial period the water content was monitored by feel. The compost was considered too wet if water could be manually squeezed out of a handful of compost and too dry if it did not feel moist to the touch (Anonymous, 2002). In the case of moisture deficiency tap water was used for irrigation until the compost had the feel of a wrung out sponge.

2.5. Process testing and validation

2.5.1. Microbiological organisms used

Salmonella, *Escherichia coli* and enterococci were monitored in the process testing in 2007 and 2008. For the validation in 2008, *Salmonella senftenberg* W 775, among the most heat resistant sero-

Table 1
Fresh matter composition in the co-composting trials of 2007 and 2008 at VUU and OA.

		PM	FW	SD	FM	C/N
		kg				Ratio
2007	VUU	169	0	0	135	15.1
	VUU	169	0	0	271	11.8
	VUU	169	0	0	406	10.4
	OA	106	0	0	67	23.4
	OA	106	0	0	135	22.5
	OA	106	0	0	202	21.7
2008	VUU	30	92	9	198	16.2

VUU, Valley View University; OA, Orphanage Africa; PM, shredded plant material; FW, food waste; SD, saw dust; FM, faecal matter.

Table 2

Physicochemical properties and inherent load of bacteria in faecal matter from two dry toilet systems in Greater Accra.

	2007		2008	
	VVU	OA	VVU	
DM (%)	29.6	16.1	21.3	
C % of DM	21.9	29.3	23.3	
N % of DM	3.3	1.8	2.8	
P % of DM	3.8	1.6	3.0	
K % of DM	1.5	4.3	1.5	
<i>Escherichia coli</i> cfu ^{-g}	1.8×10^5 (8.0×10^4 – 3.0×10^5)	1.1×10^5 (7.0×10^4 – 1.7×10^5)	1.4×10^4 (9.3×10^3 – 2.4×10^4)	
Enterococci cfu ^{-g}	1.4×10^6 (7.4×10^5 – 2.0×10^6)	1.8×10^5 (8.0×10^4 – 3.0×10^5)	8.0×10^4 (2.1×10^4 – 1.1×10^5)	

VVU, Valley View University; OA, Orphanage Africa; numbers in parentheses represent ranges detected.

Table 3

Physicochemical properties of compost structure material.

	2007		2008		
	PM (VVU)	PM (OA)	PM (VVU)	FW (VVU)	SD (VVU)
DM (%)	36.5	67.5	89.9	21.5	88.6
C % of DM	37.6	37.1	27.5	29.7	42.7
N % of DM	1.3	1.5	1.0	0.8	0.3
P % of DM	0.1	0.1	0.2	0.3	<0.1*
K % of DM	2.6	2.1	2.4	1.3	0.8

PM, shredded plant material; FW, food waste; SD, saw dust; VVU, Valley View University; OA, Orphanage Africa; numbers represent an average of three samples in 2007 and two samples in 2008, *below detection limit.

vars and non-pathogenic, was used. Further, *E. coli*, *Enterococcus faecalis* and *Ascaris suum* ova, non-pathogenic for humans, were employed for validation.

2.5.2. Process testing

In 2007 three mixed faecal matter samples, accumulated by five subsamples at the beginning of the trial and one mixed compost sample from each pile collected at day 27, 54 and 84 after experimental set-up, were analysed for *E. coli*, enterococci and salmonella. The membrane filtration method was used to enumerate bacteria (Clesceri et al., 1999). About 20 g of each faecal matter/compost was weighed into 180 ml of sterile, phosphate-buffered saline and homogenised solution. Tenfold serial dilution was performed, after which diluted samples were filtered through white, grid-marked, 47 mm-diameter, Millipore HA-type cellulose filters with a pore size of 0.45 mm. Samples were filtered using a vacuum pump and a triple glass filtration unit. The filters were placed with the grid side on Petri dishes of Chromocult coliform agar for *E. coli*, Bismuth Sulfite Agar for salmonella and M-Enterococcus Agar for enterococci. Inoculated plates were incubated for 24–48 h at 37 °C. Colonies on Chromocult agar with dark blue to violet colour were counted as presumptive *E. coli*. Black-centred light edged colonies surrounded by a black precipitate with a metallic sheen on Bismuth Sulfite Agar were counted as salmonella. Red, maroon or pink colonies were counted as presumptive enterococci. Presumptive colonies were confirmed on MacConkey No. 2 agar.

The detectable limit of bacteria with the above described methods is <3 cfu^{-g} of fresh substrate. For data expression and calculation the load was set to 0 when bacteria were not detectable.

In 2008 faecal matter was sampled accordingly during the experimental set-up (S1), analysed qualitatively for salmonella and quantitatively for *E. coli* and enterococci. The initial load of these organisms in the compost (OLco) was calculated proportionally on substrate fresh weight basis:

$$OL_{co} = \frac{OL_{fm}}{W_{fm} + W_{pm} + W_{fw} + W_{sd}}$$

where OL_{fm} is the organism load in faecal matter, W_{fm} is the weight of faecal matter, W_{pm} is the weight of the plant material,

W_{fw} is the weight of the food waste and W_{sd} is the weight of the saw dust. Composite compost samples, consisting of five subsamples each, were taken at the end of the thermophilic phase (S2 – day 27, temperatures below 55 °C in all chambers), the beginning of the stabilisation phase (S3 – day 74, temperature stabilised at ambient temperature) and at the end of the trial (S4 – day 128). The compost samples were analysed for the same organisms as the faecal matter. In addition, the quantitative load of salmonella was analysed at S3. Analytical methods were as described in the process validation below.

2.5.3. Process validation

2.5.3.1. Test containment system type 1 (TCS 1). The TCS 1 or Rapp-containment system is usually utilised for moist to liquid substrates processed in biogas plants or pasteurisation units (Rapp, 1995). The TCS 1 consists of a hollow cylinder of polycarbonate, covered on both sides with semi-permeable polycarbonate membranes, which are fixed with two tight screwable rings. The polycarbonate filter membrane allows soluble and gaseous compounds from the substrate to access the test organisms. The test container was filled with a 1:10 suspension of *S. senftenberg*, *E. faecalis* or *E. coli* and faecal sludge. The final bacterial count in the TCS 1 was between 10⁷ and 10⁸ cfu^{-g}.

The detection of the microbial indicators was carried out quantitatively using the most probable number technique (Näveke and Tepper, 1979). For the preliminary dilution, nine parts of 0.9% saline solution were added to the TCS 1 substrate and the mixture was shaken at 4 °C for 24 h. A serial dilution was then made from the preliminary dilution (1 ml in 9 ml saline solution). Enrichment was performed by transferring 1 ml of each dilution into three tubes of 9 ml MUG (4-methylumbelliferyl-β-D-glucuronide) laurel sulfate broth (*E. coli*), which were incubated at 44 ± 1 °C for 40 ± 4 h, in 9 ml azide glucose (AD) broth (*E. faecalis*) and incubated at 37 °C for 40 ± 4 h and in 9 ml buffered peptonwater (salmonella – only at S2) and incubated at 37 °C for 22–24 h. Detection of *E. coli* was characterised by the formation of gas, cleavage of MUG with the development of fluorescence and the formation of indole. All positive gas forming tubes were realkalised with 0.5 ml 1 N NaOH for reading the fluorescence. For the detection of indole, the MUG positive tubes were covered with Kovac's reagent. The incubated AD broth was spread onto kanamycin esculin azide agar (KAA agar) and incubated at 37 °C for 48 h. If growth was weak the plates were incubated for an additional 24 h. Of the peptone water, 0.1 ml was transferred into tubes of 10 ml Rappaport enrichment broth and incubated for 22–24 h at 43 °C. The enriched samples were then plated onto brilliant green phenol red saccharose agar and xylose lysine desoxycholate agar plates which were incubated at 37 °C for 22–24 h. The evaluation was carried out using the corrected MPN table according to De Man (1977).

For the qualitative detection of salmonella, the content of one TCS 1 was mixed with 450 ml of buffered peptone water and incubated for 20 h at 37 °C. Then 0.1 ml of the well-mixed

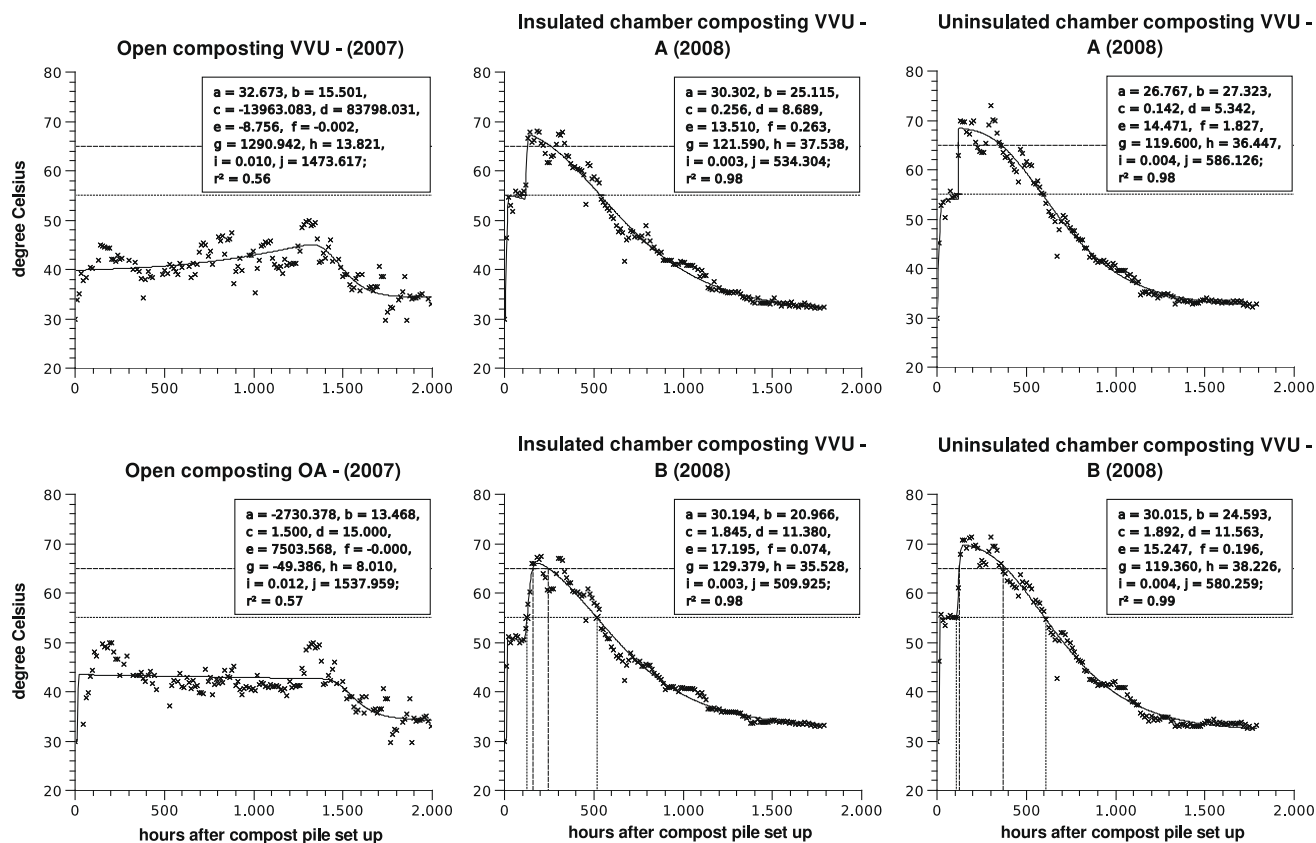


Fig. 2. Course of core temperatures during open and chamber co-composting of faecal matter. Drop lines indicate time periods with temperatures above 55 °C (punctured) and 65 °C (dashed), A and B represent the two replicates of each treatment, function of fitted curve: $y = a + b * \exp(-\exp(-c * (x - d))) + e * \exp(-\exp(-f * (x - g))) - h * \exp(-\exp(-i * (x - j)))$.

pre-enrichment is added to 10 ml Rappaport enrichment broth, incubated for 22–24 h at 37 and 43 °C. The enriched samples were then plated onto brilliant green phenol red saccharose agar and xylose lysine desoxycholate agar plates which were incubated at 37 °C for 22–24 h. Suspect colonies were plated onto standard I agar and the end identification was carried out biochemically and serologically based on the somatic and flagellar antigens (Poly I, Poly II and O19).

2.5.3.2. Test containment system type 2 (TCS 2). The TCS 2 was prepared by laying a piece of silk gauze in a funnel and filling 2 ml of *Ascaris* ova-test suspension (approximately 1 million eggs) before forming a bag and firmly tying with cable straps. For the detection of the *Ascaris* ova the TCS 2 was carefully opened and the eggs removed into a sterile petri dish with approximately 20 ml tap water. Then they were incubated at 29 °C for 3 weeks. In order to determine viability, exactly 100 ova were counted and classified as developed or not.

2.6. Data processing

A nonlinear mathematical model [$y = a + b * \exp(-\exp(-c * (x - d))) + e * \exp(-\exp(-f * (x - g))) - h * \exp(-\exp(-i * (x - j)))$] developed by Yu et al. (2008) was used for characterising the temperature time series. The first term, a , corresponds to the start and end temperature, where, a is the Ambient temperature; the second term $b * \exp(-\exp(-c * (x - d)))$ describes the temperature increase by mesophilic microbial activity, where, b is the heating potential of the mesophilic stage, c maximum mesophilic heating coefficient and d time when maximum mesophilic heating rate occurs; the third term $e * \exp(-\exp(-f * (x - g)))$ describes the

temperature increase by thermophilic microbial activity, where, e is the heating potential of the thermophilic stage, f maximum thermophilic heating coefficient and g time when maximum thermophilic heating rate occurs and the forth term $h * \exp(-\exp(-i * (x - j)))$ represents the temperature decline during microbial decay, where, h is the cooling potential, i maximum cooling coefficient and j time when maximum cooling rate occurs. Temperatures are in degree Celsius, time in hours and the coefficients without units. Data analysis and curve fitting was conducted with the Qti-Plot open source software package. Initial parameter values were set to: $a = 30$, $b = 18$, $c = 1.5$, $d = 15$, $e = 0$, $f = 0$, $g = 0$, $h = 18$, $i = 0.003$ and $j = 1500$ for 2007 and $a = 30$, $b = 25$, $c = 1.5$, $d = 15$, $e = 14$, $f = 0.2$, $g = 120$, $h = 38$, $i = 0.003$ and $j = 580$ for 2008 (estimation procedure according to Yu et al. (2008)).

3. Results

3.1. Initial microbial load

In 2007 at both sites, VVU and OA, the initial load of *E. coli* in the faecal matter was in the magnitude of 10^5 cfu^{-g} (Table 2). Enterococci counted were 10^5 cfu^{-g} at OA and 10^6 cfu^{-g} at VVU. In 2008 10^5 cfu^{-g} enterococci and *E. coli* were detected in the faecal matter at VVU. Few results of quantitative studies of these microorganisms in the collection chambers of similar toilet systems are available. The loads of *E. coli* and enterococci measured in the faecal matter are, however, in the same magnitude as found in urine diverting and composting toilet systems elsewhere under corresponding environmental conditions (Austin, 2006; Redlinger et al., 2001; Cynthia, 2005). All three faecal matter samples at VVU and OA in 2007 and 2 out of 3 at VVU in 2008 were tested positive for salmonella.

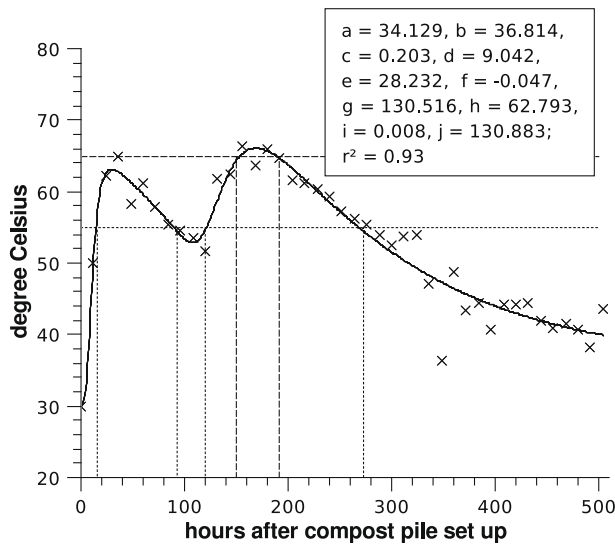


Fig. 3. Course of core temperatures of the open co-composting experiment in 2008. Drop lines indicate time periods with temperatures above 55 °C (punctured) and 65 °C (dashed), function of fitted curve: $y = a + b \cdot \exp(-\exp(-c \cdot (x-d))) + e \cdot \exp(-\exp(-f \cdot (x-g))) - h \cdot \exp(-\exp(-i \cdot (x-j)))$.

3.2. Open co-composting of faecal matter and shredded plant material

The mean core temperatures in none of the treatments at both sites exceeded 55 °C and remained largely within the upper mesophilic range (around 40 °C) for 2 months, after which they de-

creased to ambient temperature. Apart from that, there was no clear tendency in temperature development. The model used proved, due to low coefficients of determination and ambiguous regression values, to be unsuitable to describe the measured 2007 temperature time series (Fig. 2). For about 1 month, temperatures in the core remained up to 15 °C higher than that in the outer layers. This difference was positively correlated to the core temperature. During the first 6 weeks of composting the cumulative precipitation was 140 mm with one rainfall event exceeding 30 mm, but no distinct change of temperature was recorded after any rainfall event.

The reduction of faecal indicators during the 84-day course of observation was poor without any significant difference between the treatments and sites. The initial load of *E. coli* was reduced by less than one log₁₀-unit to $>4.4 \times 10^4$ cfu^{-g} and enterococci by 4–5 log₁₀-units to 1.3 – 2.5×10^4 cfu^{-g}. All final compost samples were tested positive for salmonella and quantitative analysis revealed loads in the magnitude of 3.0×10^4 cfu^{-g}.

3.3. Chamber co-composting of faecal matter with food waste and shredded plant material

3.3.1. Temperatures

Temperatures in the compost core of the insulated and uninsulated chambers quickly rose above ambient to between 50 and 55 °C. The typical discontinuity of increasing temperatures during the transition from mesophilic to thermophilic composting (Epstein, 1997) is distinctly expressed in the temperature curves of all chambers. Peak heat, above 65 °C, was achieved in the second week of composting, after which declining temperatures were measured in all chambers. The course of temperature in all chambers is accurately described by the mathematical function fitted ($r^2 > 0.98$ for all four chambers, Fig. 2).

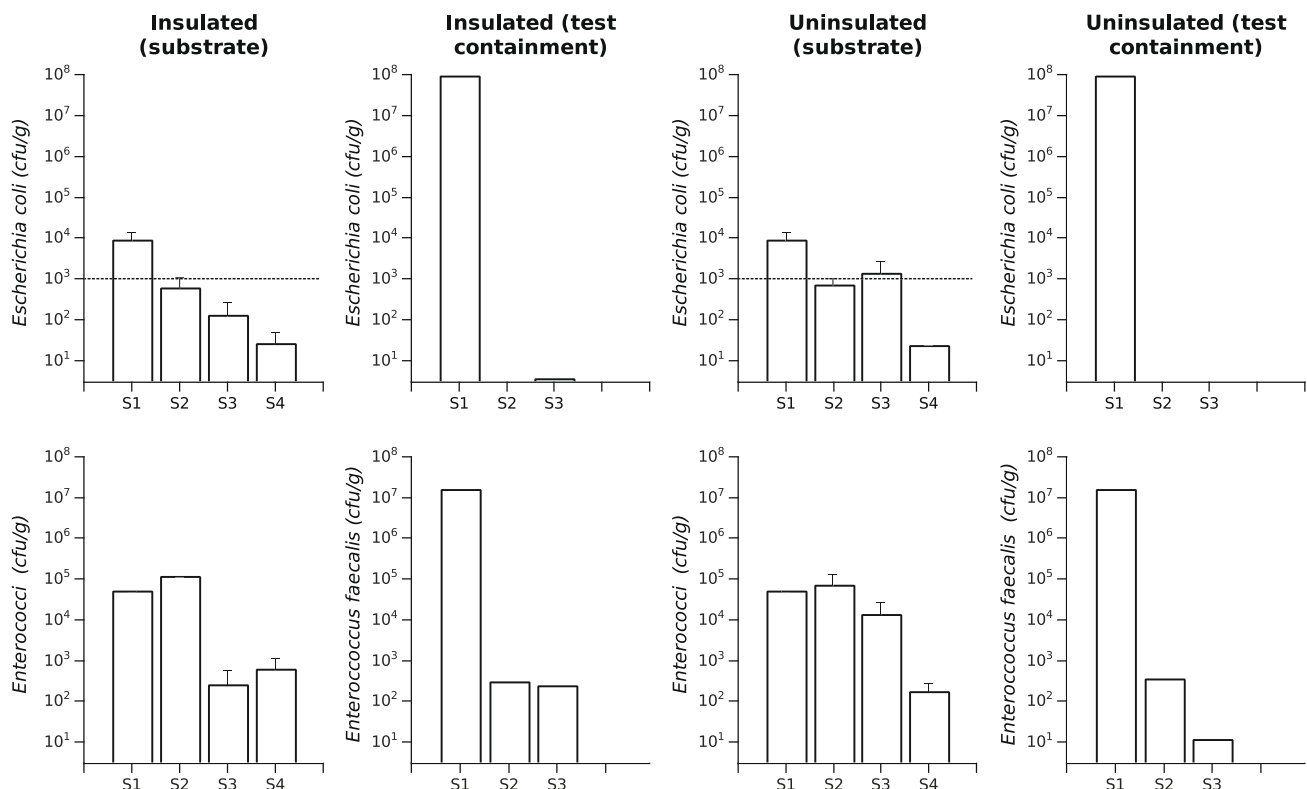


Fig. 4. Reduction of viable *E. coli*, *E. faecalis* and Enterococci in compost substrate and test containment systems during co-composting of faecal matter. S1, S2, S3 and S4 on the x-axis indicate 0, 27, 74 and 128 days after compost pile set up. The punctured line represents the common threshold value of 1000 cfu *E. coli* per gram of compost.

The German biowaste directive demands minimum compost temperatures of 55 °C for a period of 14 days or of 65 °C for 7 days (BioAbfV, 2006). These sanitisation periods are in accordance with most international composting standards (Hogg et al., 2002a; Noble and Roberts, 2004). The fitted temperature curves show that the 55 °C specification was fulfilled in the core of all chambers. Core temperatures exceeding 65 °C for over 7 days were only achieved in the uninsulated chambers (UC). Also, the 55 °C requirement was achieved in the outer compost layer of the UC, but not of the insulated chambers (IC).

Temperatures in the open compost pile observed in parallel decreased to below 55 °C within less than 14 days. During this time there was no significant difference in the average temperature in comparison to the chambers, but high core temperatures were not continuous as the temperature dropped below 52 °C after the first mixing (Fig. 3). The mean difference between core and outer layer temperatures was 9.1 ± 3.6 °C. Corresponding temperature differences in the UCs were 3.5 ± 3.0 and 4.1 ± 4.0 °C and in the ICs 1.8 ± 3.8 and 2.6 ± 3.7 °C.

3.4. Microbiological parameters

3.4.1. *Escherichia coli*

In the compost substrate of all chambers *E. coli* was continuously decimated to below 2 log10-units (Fig. 4). In both chamber types *E. coli* in the TCS 1 was completely deactivated after 1 month. In one of the four TCS 1 removed from the IC after 2.5 months a load of 3.6 cfu^{-g} was found, while no viable *E. coli* was detected in any of the other TCS 1.

3.4.2. *Enterococci* and *E. faecalis*

The load of enterococci in the combined substrate of both treatments was lowered by 2–3 log10-units (Fig. 4). The *E. faecalis* population in the TCS 1 of the UC was reduced by over 5 log10-units. In the IC the decrease was slightly less than in the UC, but also in the magnitude of 5 log10-units.

3.4.3. *Salmonella*

All mixed compost samples at sampling date S2 and the IC samples at S3 were tested Poly II positive. One UC sample was Poly I positive and in the other one no antigens were detected at S3. At S4 all samples were tested negative for salmonella antigens, except one from the IC that was Poly I positive.

In quantitative analyses of the IC samples taken at S3, 2×10^2 – $9 \times 10^3 \text{ cfu}^{-g}$ salmonella were found. The salmonella load was below the detection limit in UC. At S4 no salmonella were detected in any of the samples.

The inoculated TCS 1 validation probes tested positive to 50% in IC and 75% in UC at S2 and negative to 100% at S3.

3.4.4. *Ascaris suum ova*

The viability of *Ascaris ova* at S3 was 91% in an untreated control. Ova recovery from all IC and two of the UC TCS 2 probes was insufficient for a robust statement. A viability of 0% was observed in the remaining two IC probes.

4. Discussion

Open co-composting of faecal matter with shredded bush vegetation did not produce enough heat to comply with current international composting regulations. Sufficiently high temperatures were achieved in compost chambers under the addition of food waste to the substrate. It is assumed that the additional heat production is primarily associated with the availability of easily digestible compounds contained in the food waste. The

importance of these compounds, including sugar, starch and lipids or fats, in the composting process is well documented (e.g. Poincelot, 1974; Ruggieri et al., 2008). High microbial activity coincides with fast decomposition of starch and fat and, regardless of the minor proportion, these energy sources are important carbon substrates for the growth of thermophilic microorganisms during composting (Steger et al., 2005). Quickly falling temperatures indicate the exhaustion of easily degradable substrate compounds (Yu et al., 2008). Food waste as source of these compounds has also a value as fodder and is limited in its availability, therefore future research should identify the minimal amount of food waste needed for successful small scale co-composting of faecal matter. No impact of different C:N ratios on the temperature development was detected in 2007. The minimal amount carbon rich structure material for sufficient aeration and the optimal proportion for nitrogen conservation should also be investigated.

From comparison with temperature curves of 2007 and the parallel open composting observation in 2008, it can be concluded that apart from facilitating management, especially humidity, the advantage of the chambers is primarily a more stable core and a higher temperature of the outer compost layer. Further, regulatory temperature requirements for organic waste composting in vessels are generally lower (Hogg et al., 2002a). There is, however, little agreement on vessel specifications, especially in backyard composting (Alexander, 2007). Results from a faecal matter plus food waste co-composting experiment in Uganda suggest that insulation is necessary to achieve sanitising temperatures also under tropical conditions (Niwagaba et al., 2009). While chambers improved the temperature course, there was no additional advantage of insulation in our experiment. The temperatures during the sanitisation phase were constant, and slightly lower in the IC than in the UC. The insulation reduced gaseous exchange by blocking gaps in doors and in the roof of the ICs, which is assumed to have limited microbiological activity. A potential impact of the anti-bacterial activity of neem leaves and branches (Hoque et al., 2007) on microbiological activity and temperature development in 2007 is uncertain and needs further investigation.

The reduction of the common indicator organisms salmonella and *E. coli* was insufficient in the open composting trial to comply with current composting standards. Most of these require salmonella below the detection limit and an *E. coli* load below $1 \times 10^3 \text{ cfu}^{-g}$ (e.g. Hogg et al., 2002b; BioAbfV, 2006). Due to the fact that during the trial period hardly any reduction in salmonella and enterococci was observed, it is also unlikely that acceptable levels would have been reached within an extended stabilisation phase of the 2007 experiment.

The thermal treatment during the sanitisation phase of IC and UC alone proved inadequate to reduce the microbiological indicators sufficiently for unrestricted use in agriculture. While the process validation showed that core temperatures were high enough to inactivate *E. coli*, *E. faecalis* and *Ascaris ova*, a few viable *S. senftenberg* were detected quantitatively in two TCS 1 of the IC. Further, the load of *E. coli* in one UC sample remained too high. A substantial *E. coli* regrowth and recolonisation from the cooler outer layers seems to interfere with the sanitisation efficiency (Zaleski et al., 2005). The increase of faecal indicator populations in compost is closely associated with the availability of digestible carbon and low competitive microbiological diversity (Soares, 1996). Therefore, the regrowth ability of the indicator organisms indicates compost immaturity at the end of the sanitation phase (period of temperatures above 55 °C, Fig. 2). Towards the end of the stabilisation phase about 1750 h after compost set up, all microbiological parameters were within the required ranges (Fig. 4), except for the qualitative detection of salmonella in one compost sample of the insulated chambers.

Our results suggest that: (a) for sufficient heat generation during small scale faecal matter co-composting with shredded bush vegetation, the addition of easily digestible energy sources, such as food waste, is required. (b) The confinement in compost chambers increases and stabilises the course of temperature. (c) Additional insulation of simple compost chambers does not increase temperature or improve sanitisation. (d) The thermophilic phase must be combined with a stabilisation phase for sufficient reduction of microbial indicator populations.

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References

- Alexander, P., 2007. Effect of turning and vessel type on compost temperature and composition in backyard (amateur) composting. *Compost Science and Utilization* 15 (3), 167–175.
- Anonymous, 2002. Measuring moisture by feel. *BioCycle* 43 (2), 49.
- Austin, L.M., 2006. Operational safety of urine diversion toilets in Durban, South Africa. In: *Proceedings of the 32nd WEDC International Conference*, Colombo, Sri Lanka, pp. 13–17.
- BioAbfV, 2006. Bioabfallverordnung (Verordnung über die Verwertung von Bioabfällen auf landwirtschaftlich, forstwirtschaftlich und gärtnerisch genutzten Böden). *Bundesgesetzblatt*, Germany.
- Clesceri, L.S., Greenberg, A.E., Eaton, A.D. (Eds.), 1999. *Standard Methods for Examination of Water and Wastewater*. American Public Health Association, Washington, USA.
- Cynthia, P.M., 2005. Health and Safety Aspects of the Use of Products from Urine-diversion Toilets. M.Sc. Thesis. Faculty of Natural and Agricultural Sciences, University of Pretoria, Pretoria, South Africa.
- Danso, G., Drechsel, P., Fialor, S., Giordano, M., 2006. Estimating the demand for municipal waste compost via farmers' willingness-to-pay in Ghana. *Waste Management* 26 (12), 1400–1409.
- De Man, J., 1977. MPN tables for more than one test. *European Journal of Applied Microbiology* 4 (4), 307–316.
- Epstein, E., 1997. *The Science of Composting*. Technomic Pub. Co., Lancaster, PA, USA.
- Esrey, S.A., Andersson, I., Hillers, A., Sawyer, R., 2001. Closing the Loop – Ecological Sanitation for Food Security. Sida and UNDP, Mexico.
- Hogg, D., Barth, J., Faviono, E., et al., 2002a. Comparison of Compost Standards within the EU, North America, and Australasia. Main Report. The Waste and Resources Action Programme, Banbury, UK.
- Hogg, D., Barth, J., Faviono, E., et al., 2002b. Review of Compost Standards in the UK. Supplement to Main Report: Comparison of Compost Standards within the EU. North America and Australasia. The Waste and Resources Action Programme, Banbury, UK.
- Höglund, C., 2001. Evaluation of Microbial Health Risks Associated with the Reuse of Source-separated Human Urine. Ph.D. Thesis. Royal Institute of Technology, Swedish Institute for Infectious Disease Control, Stockholm, Sweden.
- Hoque, M., Bari, M., Inatsu, Y., Juneja, V., Kawamoto, S., 2007. Antibacterial activity of guava (*Psidium guajava* L.) and neem (*Azadirachta indica* A. Juss.) extracts against foodborne pathogens and spoilage bacteria. *Foodborne Pathogens and Disease* 4 (4), 481–488.
- Illmer, P., 2002. Backyard composting: General considerations and a case study. In: Insam, H., Klammer, S., Nuntavan, R. (Eds.), *Microbiology of Composting*. Springer, Berlin, Germany, pp. 133–142.
- Näveke, R., Tepper, K., 1979. Einführung in die mikrobiologischen Arbeitsmethoden. Urban und Fischer, München, Germany.
- Niwagaba, C., Nalubega, M., Vinnerås, B., Sundberg, C., Jönsson, H., 2009. Bench-scale composting of source-separated human faeces for sanitation. *Waste Management* 29 (2), 585–589.
- Noble, R., Roberts, S., 2004. Eradication of plant pathogens and nematodes during composting: a review. *Plant Pathology* 53 (5), 548–568.
- Poincelot, R., 1974. A scientific examination of the principles and practice of composting. *Compost Science* 15 (3), 24–31.
- Rapp, A., 1995. Hygienisch-mikrobiologische Untersuchungen zum Verhalten von ausgewählten Bakterien und Viren während der längerfristigen Speicherung von Flüssigmist in Güllegemeinschaftsanlagen. Ph.D. Thesis. Universität Hohenheim, Stuttgart, Germany.
- Redlinger, T., Graham, J., Corella-Barud, V., Avitia, R., 2001. Survival of fecal coliforms in dry-composting toilets. *Applied and Environmental Microbiology* 67 (9), 4036–4040.
- Richard, D., Zimmerman, R., 1995. Respiration rate – reheating potential: a comparison of measures of compost stability. *Compost Science and Utilization* 3 (2), 74.
- Ruggieri, L., Gea, T., Artola, A., Sánchez, A., 2008. Influence of different co-substrates biochemical composition on raw sludge co-composting. *Biodegradation* 19 (3), 403–415.
- Schaefer, M., 2008. Water technologies and the environment: ramping up by scaling down. *Technology in Society* 30 (3–4), 415–422.
- Soares, H.M., 1996. Pathogen Indicator Regrowth Potential as a Method to Evaluate Compost Stability. Ph.D. Thesis. University of Massachusetts Amherst.
- Starkl, M., Binner, E., Fürhacker, M., Holubar, P., Koeck, S., Lenz, K., et al., 2005. Nachhaltige Strategien der Abwasserentsorgung im ländlichen Raum. Bundesministerium für Land- und Forstwirtschaft, Umwelt und Wasserwirtschaft, Wien, Austria.
- Steger, K., Ekland, Y., Olsson, J., Sundh, I., 2005. Microbial community growth and utilization of carbon constituents during thermophilic composting at different oxygen levels. *Microbial Ecology* 50 (2), 163–171.
- Vinnerås, B., Björklund, A., Jönsson, H., 2003. Thermal composting of faecal matter as treatment and possible disinfection method – laboratory-scale and pilot-scale studies. *Bioresource Technology* 88, 47–54.
- WHO, UNICEF, 2006. Meeting the MDG Drinking Water and Sanitation Target: The Urban and Rural Challenge of the Decade. WHO, UNICEF, Geneva, Switzerland.
- Yu, S., Clark, O., Leonard, J., 2008. A statistical method for the analysis of nonlinear temperature time series from compost. *Bioresource Technology* 99 (6), 1886–1895.
- Zaleski, K., Josephson, K., Gerba, C., Pepper, I., 2005. Survival, growth, and regrowth of enteric indicator and pathogenic bacteria in biosolids, compost, soil, and land applied biosolids. *Journal of Residuals Science and Technology* 2, 49–63.